Arnold Schwarzenegger
Governor

EMISSIONS MARKETS—CHARACTERISTICS AND EVOLUTION

PIER PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
University of California, Berkeley

March 2005
CEC-500-2005-024

California Climate Change Center
Report Series Number 2005-011

Prepared By:
University of California, Berkeley
Alexander E. Farrell
Berkeley, California
Contract No. 500-02-004

Prepared For:
California Energy Commission
Public Interest Energy Research (PIER) Program

Guido Franco,
Contract Manager

Kelly Birkinshaw,
Program Area Team Lead
Energy-Related Environmental Research

Ron Kukulka,
Acting Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert L. Therkelsen
Executive Director

Acknowledgements

The author would like to thank Guido Franco of the California Energy Commission, as well as Michael Hanemann and Alan Sanstad of the California Climate Change Center for support, suggestions, and other encouragement.

Please cite this report as follows:

Farrell, Alexander E. 2004. *Emissions Markets—Characteristics and Evolution.* University of California, Berkeley, for the California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2005-024.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

The California Climate Change Center (CCCC) is sponsored by the PIER program and coordinated by its Energy-Related Environmental Research area. The Center is managed by the California Energy Commission, Scripps Institution of Oceanography at the University of California at San Diego, and the University of California at Berkeley. The Scripps Institution of Oceanography conducts and administers research on climate change detection, analysis, and modeling; and the University of California at Berkeley conducts and administers research on economic analyses and policy issues. The Center also supports the Global Climate Change Grant Program, which offers competitive solicitations for climate research.

The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, these reports receive minimal editing, and the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

The work described in this report was conducted under the Preliminary Economic Analyses of Climate Change Impacts and Adaption, and GHG Mitigation contract, contract number 500-02-004, WA MR-006, by Alexander E. Farrell, at the University of California, Berkeley.

For more information on the PIER Program, please visit the Energy Commission's Web site www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-4628.

Table of Contents

Abstract

In contrast to most other public policies, emission trading programs generally create an explicit market in an environmental good, and the functioning of this market is an important factor in determining the overall effectiveness and efficiency of the emission trading policy. *Emissions Markets – Characteristics and Evolution* discusses the development, evolution, and performance of an emissions market for nitrogen oxides that was created in 1999 for electric power plants and other large sources in several northeastern states. It provides a history of the evolution of this market, evaluates the role of uncertain and complex regulatory provisions on market participation and program effectiveness. The main findings are that this emissions trading program achieved its proximate goal of reducing emissions despite several imperfections in program design, that this market was quite thin (i.e., saw relatively few transactions) that limited its efficiency, and that it had relatively little effect on the cost of electricity or the behavior of electricity producers. This research implies that interstate emission trading programs can be successfully designed, but that it could be very helpful if allowance price information was reported early and routinely and that efforts to encourage trading might increase efficiency.

Keywords: Emission trading, markets, allowances, auction, transaction, behavior

1. Introduction

A variety of efforts are currently underway at the local, state, national, and international levels to attempt to mitigate greenhouse gas (GHG) emissions and to stimulate the technological innovation that will be necessary to avoid dangerous climate change. Among these are the consideration of using market-based incentives (MBIs) to regulate GHG emissions, and in particular, emissions trading.

The first type of emission trading system is based on a facility-specific baseline and provides for the opportunity for facilities to operate above or below their baseline by using credits. These are called "baseline and credit" or "emission reduction credit" (ERC) programs. These programs have been modestly successful in reducing emissions and costs, but they generally do not yield significant transactions between different firms. Most of the emission trading is intrafirm, and often takes place between different units located at a single large facility. To a large degree this is driven by high transaction costs and various regulatory barriers, which are discussed in another California Climate Change Center report (Farrell 2004).

The second type of emission trading system is known as cap-and-trade (C/T), which, as the name implies, creates a permanent limit on emissions. In a C/T system, the government defines the regulated sources and the total amount of pollution that they can emit during a set period—the "cap." Typically, the cap is set in mass units (e.g., tons), is lower than historical emissions, and declines over time. The government creates allowances equal to the size of the cap and then distributes them to the regulated sources—a process called *allocation.* The government then requires regulated facilities to surrender emission allowances equal to the emissions of the facilities on a periodic basis (sometimes called "true up"). It will also set standards for emissions monitoring and establish rules for how allowances may be used and for enforcement measures. To date, most major emission markets are C/T markets. The only exception is the international carbon dioxide (CO_2) market, in which contracts somewhat like ERCs are sold in the expectation that they will eventually be usable in an international C/T program developed as part of the Kyoto Protocol.

Because the allocation to each firm is smaller than its previous emissions, regulated firms have four basic options: (1) control emissions to exactly match their allocation; (2) undercontrol and buy allowances to cover their emissions; (3) overcontrol and then sell their excess; or (4) overcontrol and bank allowances for use in future years (when even fewer allowances will be allocated). The reason companies might buy or sell allowances is that facilities will have different emission control costs, or they might change operations so that they need more (or fewer) allowances. Firms with higher costs could save money by undercontrolling and buying allowances from those with lower costs, which could make money by overcontrolling and selling allowances.

Governments regulate the trading of emissions allowances differently in various C/T systems. The government usually acts as the accountant for C/T systems by establishing a registry for participants. Usually, participants must report the size of transactions and the names of the buyer and seller. This process can be facilitated by creating a serial number for each allowance. However, there is often no requirement that market participants disclose the price at which a sale was made, nor any requirement that they inform government of the trade in a timely manner. This lack of information can limit the transparency of the market, as participants may delay reporting trades in order to conceal strategic information. Brokerage and consulting firms complete the picture by providing services to market participants, including small markets in derivative commodities, and by increasing transparency by providing information about the markets. Simplicity in market design and competition among brokers has tended to keep transaction costs low (up to a few percent of allowance prices) in emission allowance markets.

Fuel combustion is a leading source of nitrogen oxides (NO_x), which can lead to important effects on human health and the environment, including elevated concentrations of ground-level ozone (i.e., photochemical smog), fine airborne particles (solids less than 2.5 microns in diameter), acidification, eutrophication, and even climate change (National Research Council - Committee on Tropospheric Ozone Formation and Measurement 1991; Metcalfe et al. 1998; Burtraw et al. 2001; Shindell et al. 2003). The air pollution effects of NO_x emissions are most pronounced at high temperatures and in bright sunlight, which in the eastern United States means the summer time.

Originally thought to be a local problem, evidence of the regional nature of ozone began to emerge in the mid-1970s, and by the 1980s the phenomenon of "ozone transport" was widely recognized (National Research Council - Committee on Tropospheric Ozone Formation and Measurement 1991). A key implication was that regional policies were needed, and this led to the Ozone Transport Commission (OTC). The OTC was established under the Clean Air Act Amendments of 1990 to help the Northeast and Mid-Atlantic region[1] reduce harmful ground-level ozone, specifically by reducing NO_x emissions that lead to ozone formation. Similar to the case for SO_2 at the national level, these state regulators turned to emission trading as the key strategy for controlling NO_x emissions from large stationary sources. OTC states implemented a strategy in three phases. Phase 1 began in 1995 and relied on traditional technology standards.[2] Phase 2, which began in 1999, marked the beginning of emissions trading. Nine of the OTC states and the District of Columbia launched a cap-and-trade system called the "OTC NO_x Budget Program," a central topic in this report. Figure 1 shows where this policy was implemented. Phase 2 lasted four years, from 1999 to 2002. Phase 3 was scheduled to begin in 2003 and was marked by continued emissions trading but with more stringent emissions reductions. As it turned out, a broader federal program known as the "NO_x SIP Call" merged with Phase 3 and subsumed the OTC NO_x program into a super-regional trading system for the eastern United States. This report evaluates the evolution of the NO_x Budget market and the start of the subsequent NO_x SIP Call market.

This report focuses on the markets that have emerged around cap-and-trade systems, focusing on organization, participation, and how firms have interacted with emission markets. The goal of the report is to provide insights into how GHG emission markets in California might work.

The report is laid out as follows. Section 2 describes the background and general progress of the OTC NO_X Budget Program, and the associated allowance market. Section 3 describes an econometric of the market for OTC NO_X Budget allowances and the underlying electricity market. Section 4 presents the results of the analysis, and Section 5 contains the report's conclusions.

---

[1] The OTC consists of representatives from Connecticut, Delaware, District of Columbia, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Virginia.
[2] Specifically, these standards were known as "Reasonably Available Control Technology," or RACT.

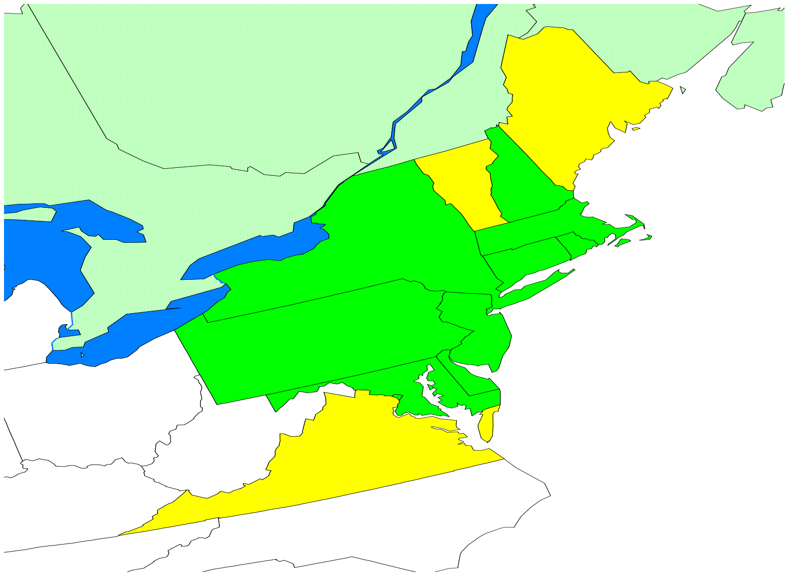

Figure 1. Sates in the Ozone Transport Region
Green: States in the OTC NO_x Budget Program
Yellow: States not the NO_x Budget Program

2. History of the NO_X Budget Emission Market

The OTC NO_x Budget had several distinctive features in relation to the development of its allowance market. First, there were three phases of the program. Phase 1 adopted the existing federal RACT performance standard, while Phases 2 and 3 evolved into progressively stringent emission trading. Second, the OTC NO_x Budget had no methods for early price discovery before it went into effect. These have proved important in other markets (Ellerman et al. 2000 pp. 161–165, 174–176). For instance, the Acid Rain program for SO_2 had a set of auctions several years before the start of the regulatory period. Although these auctions were criticized for not providing the most accurate and useful price information, they were informative to market participants and facilitated start-up of the program. Third, banked allowances in the OTC NO_x Budget were slightly discounted because of a regulatory provision known as "progressive flow control" (PFC), which was designed to prevent spikes in emissions that would exacerbate ozone formation.

The price of NO_x allowances were forecast by the U.S. Environmental Protection Agency (EPA), various consultants, and other researchers. Generally, the costs in Phase 2 were expected in the range of $1,200–$2,400 per ton (i.e., per allowance), and costs in Phase 3 were in the range of $2,500–$3,500 (STAPPA/ALAPCO 1994; ICF Resources 1995; Dorris et al. 1999; Farrell et al. 1999). Specific forecasts depended on highly variable factors such as the relative prices of gas and coal, but were bounded to some extent by relatively well-understood economics of NO_x control engineering and technologies. By the time that NO_x trading started in 1999, the RACT implementation phase has already captured a significant amount of "low hanging fruit," or low-cost emissions reductions, specifically through the use of low-NO_x burners, sometimes in combination with overfire air. These control options were relatively cheap. For large coal-fired utility boilers, costs were in the range of $100–$400 per ton of NO_x reduced (EPRI 2000), while costs for industrial boiler retrofits were under $800 per ton (Amar and Staudt 2000). Once RACT implementation was complete, though, the remaining technology options for achieving additional reductions, such as selective catalytic reduction, were more expensive. The advent of trading was intended to provide flexibility to help alleviate the higher projected costs associated with these technologies.

Figure 2 shows the prices for NO_x allowances in the OTC NO_x Budget market over the period 1998 to early 2004. Although there was significant price volatility at the outset in 1999, most NO_x allowances sold for prices well below the forecasts. Since 2003, the market functioned within the NO_x SIP Call. The effects of the changes in program status are visible. Note that trading occurs year-round, even though NO_x allowances are only required to cover emissions during the May to September ozone season.

A small amount of emission trading began in early 1998 as some regulated sources came to believe that the program would go ahead and that they could take advantage of the opportunity to either lower costs or perhaps even generate revenue through allowance transactions. Trades began at about the level that most forecasts had predicted, approximately $1,500/ton of NO_x. During the middle of 1998, it became clear that most OTC states would in fact implement the NO_x budget in 1999. By the end of 1998 and the beginning of 1999, average monthly allowance prices had risen to over $5,000/ton, far above the cost of control for any regulated sources.

Market participants thought that the market was "short," meaning that regulated firms might not have installed enough emissions control equipment in aggregate to meet the cap.

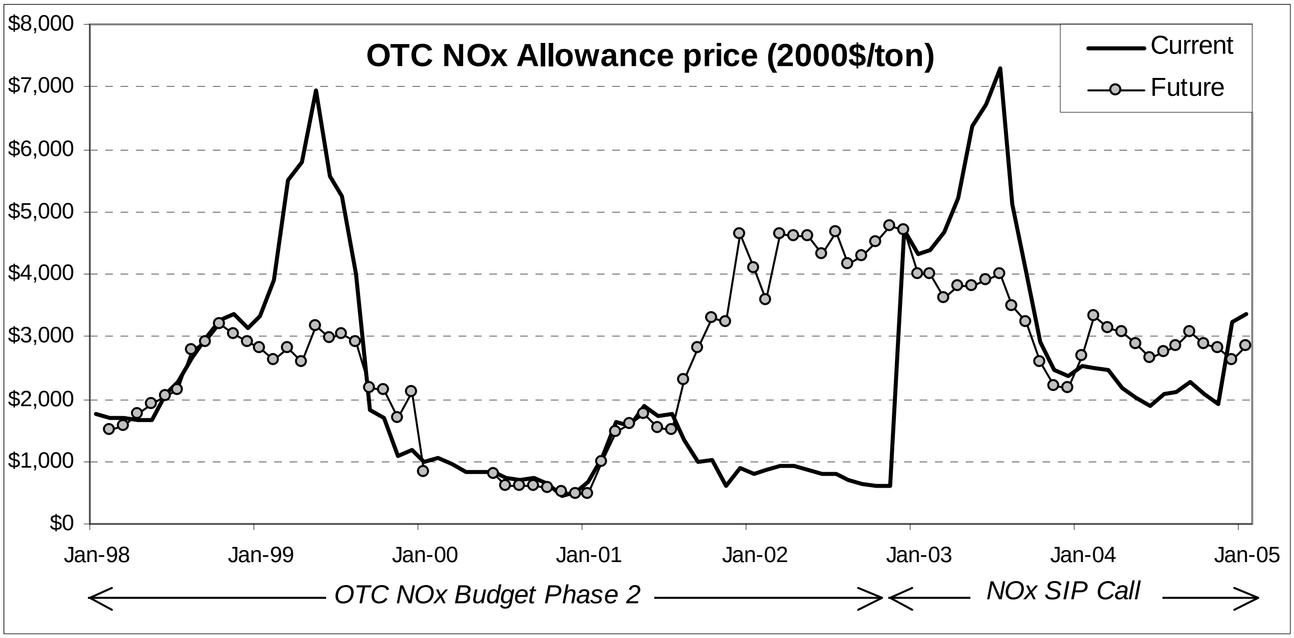

Figure 2. Prices in the OTC NO_X market declined in each phase (real 2000$ dollars)

As this realization occurred near the end of 1998, there was insufficient time to install control equipment for the upcoming ozone season. It also seems that some participants in the NO_x market were surprised to find that the experience of the SO_2 market (low prices and an abundant supply of allowances) was not repeated. These factors added up to a tight allowance market with insufficient supply of allowances relative to demand. Allowance prices naturally rose. Importantly, only a few "economically significant" trades (i.e. trades between different firms), occurred during this period of high prices.

Prices stayed high for several months, but by July 1999 had fallen back to the predicted range, and by the end of the year fell to around $1,000/ton. Several factors accounted for this fall. First, early reduction allowances began to enter the market, starting with New Hampshire allowances in early April, followed by large distributions to New York and New Jersey. This dramatically expanded allowance supply. Second, several firms found that, given incentives, they could install additional emissions control equipment in a more timely fashion. Unexpected and much faster-than-normal installations of controls on plants in Massachusetts, New Hampshire, New Jersey, and Pennsylvania reduced demand. Third, a Maryland lawsuit reduced demand further by taking power plants that were expected to be net buyers of allowances out of the market, albeit temporarily.

The response of state governments and regulated sources during the early price spike illustrates more of the advantageous features of cap-and-trade systems. Regulators stood by the market system despite the high prices, while firms used the markets to work out their difficulties rather than seek legal challenges in the courts. In a command-and-control system, uncertainty and delays would potentially cause industry to seek such "regulatory relief," which in turn would reduce the environmental effectiveness of the program. While a few firms experienced higher costs, others gained a windfall, although overall the effect was relatively small. Most importantly, the OTC NO_x Budget provided powerful economic signals that prudent management of NO_x emissions could reduce compliance costs.

Subsequently, the OTC NO_x market matured. Emission trading became more common and price volatility declined. For the remainder of the period that the OTC NO_x Budget was in force (2000–2002), prices averaged somewhat below $1,500/ton. In addition, a difference in prices for banked and current-year allowances developed to reflect the flow control restrictions on using banked allowances. Thus, the market was able to adapt readily to a complex regulatory issue. Most of the allowances sold in 1999–2002 for Phase 2 of the program traded at prices below the range that had been forecasted prior to implementation.

By the middle of 2001, regulated sources were already looking ahead to the more stringent cap that would be in place in 2003, the Phase 3 period. Although it was expected, and later proved to be true, that Phase 3 would be replaced by the NO_x SIP Call, regulators in the OTC states had begun to issue rules for how banked allowances from the OTC NO_x Budget would be converted to use for NO_x SIP Call compliance. Again, the market adapted readily.

However, a similar pattern of industry lawsuits and other delaying maneuvers also emerged from some of the firms that were newly regulated under the NO_x SIP Call. The resulting pattern of expectations and court-issued complications to the original regulations led to uncertainty that drove prices up again, this time over $7,000/ton. Again, this was higher than predicted. In addition, uncertainties about the performance of new emission control technologies added to the desire of some regulated sources to purchase allowances. By early 2003, allowances in the NO_x SIP Call market itself had started to trade at relatively high prices, about $4,000/ton, for similar reasons. However, these prices quickly fell to the $2,000–$3,000 range, which is at the low end or below the range predicted prior to implementation.

By the end of the summer of 2003, it had become clear that there would be no serious shortfall of allowances for that season, and firms began to turn more of their attention to the 2004 and subsequent ozone seasons. One indication of this is the sharp narrowing of the gap between the 2004 and 2005 prices, and the reversal of the gap in November. Since that time, the prices of what are effectively banked allowances have been discounted by about $1,000/ton. The reason for the discount is that the states apply various limitations on how OCT NO_x Budget allowances, of which a significant bank exists, can be used in the NO_x SIP Call. This sort of transition had occurred earlier in the OTC NO_x Budget when new sources (e.g., those in Maryland) had been added.

As the emission market entered 2004, a major transition was expected as the SIP Call states began to be added.[3] The exact schedule was complex, some entered in 2004, some not until 2007, and not all NO_x emitters in all states were included. A key issue is that allowances were allocated for most of the five-month emission season, but due to a lawsuit, some firms were only

[3] These states included the OTC NO_X Budget states, plus Indiana, Illinois, Kentucky, North Carolina, Ohio, South Carolina, Tennessee, Virginia, West Virginia, and parts of Alabama, Georgia, Michigan, and Missouri.

regulated for the four months June–September. This created a significant excess of allowances in 2004. In addition, states used several mechanisms to ease the transition. One was a type of set-aside called a Compliance Supplement Pool, which amounted to about 140,000 allowances for all the NO_x SIP Call states. One effect of this pool was to reduce demand for allowances by firms that were not capable of reducing emissions below their allocations, which would tend to reduce allowance prices and reduce the number of allowances transacted. In addition, during 2004, several states held auctions of several thousand allowances.

2.1 Industrial Source Participation

In addition to electric generating units (EGUs), the OTC NO_x Budget program also regulated some industrial operations, including over 120 unique emissions sources located at 43 facilities. A wide variety of industries were included, such as petroleum refining, pulp and paper, and "electric, gas, and sanitary services," an eclectic group of facilities such as cogeneration and central steam plants.

Industrial sources had declining emissions throughout the 1999–2002 period. Emissions were consistently lower than annual allocations by an average of 20%. In reducing emissions, sources displayed flexibility in a wide range of compliance strategies, including switching to cleaner fuels, modifying production processes, boiler replacements, combustion modifications, installation of control technologies, and unit retirement or deferment (Office of Air and Radiation 2003, Ozone Transport Commission 2003). Industrial sources were also active buyers and sellers of allowances. Some firms even gained net profits from trading (Swift 2001), while others found greater operational efficiency as a result of the new emissions monitoring systems.

More telling is the fact that industrial sources sold 9% of their allowances to EGUs and market participants, suggesting that, in aggregate, industrial sources had lower control costs than EGUs. This is not surprising, given the breadth of control options that industrial sources employed. "The response portfolio of industrial plants is considerably broader than that of traditional EGUs that simply sell their power, as it includes modification in their base technology as well as their power source, and so may make it easier for industrial sources to develop low-cost responses" (Swift, 2001). By including industrial sources in the NO_x trading program, the OTC was able to improve flexibility, achieve greater reductions in emissions, and lower overall program costs.

Perhaps the greatest challenge for industrial sources, however, was the monitoring and reporting requirements. Unlike large EGUs, these sources did not have continuous emissions monitors (CEMS) in place, and therefore had to develop or modify NO_x emissions measurement systems, which often required software upgrades to plant control systems.

2.2 Progressive Flow Control

One of the OTC NO_x Budget's most distinctive features was an unusual limitation on trading, called "progressive flow control" (PFC). Under these rules, several months after the true-up date for the relevant control period, regulators determine the discount factor for all banked allowances for the upcoming year. Although a relatively straightforward formula is used to determine the discount factor, it is based on aggregate behavior of all firms that hold allowances, so individual firms do not know what (if any) discount will be applied to their allowances until after they have made decisions about banking allowances. This adds an element of uncertainty to the allowance market.

The intent of PFC is to deal with the episodic nature of photochemical smog (commonly measured in terms of ozone concentrations) in the northeastern United States (Possiel and Cox 1993). Smog is a secondary pollutant, formed from precursor compounds, of which NO_x is the most important in the OTC region (Milford et al. 1994). Unhealthful smog levels occur in the OTC region on only a limited number of days (usually < 20 per year), which occur when meteorological conditions are most favorable for smog formation and accumulation. These are typically hot summer days when anthropogenic NO_x emissions also tend to rise as electric power plants increase generation to meet air conditioning demand. Progressive flow control was implemented to limit the use of banked allowances out of concern that if one or two cool summers was followed by a hot summer, firms would build up a significant number of allowances that could allow them to emit more NO_x than the capped level, possibly allowing firms to comply with the requirements of the program without achieving its goals.

Concerns about temporal and spatial effects have influenced other emission trading markets as well. For instance, the RECLAIM program had two trading zones as well as a policy that did not allow banking from one year to another—features that addressed each of these issues (Fromm and Hansjurgens 1996). Some local emission reduction credit programs feature sunset provisions for credits. The debate about the Clean Air Act's Acid Rain Program for SO_2 featured a spatial limitation almost to the end, and the current Clear Skies Initiative features spatial limitations (Nash and Revesz 2001 pp. 589–593; Bush 2002). Some experts feel this is an inherent problem of C/T systems and several solutions have been proposed, including trading zones, markets in units of environmental degradation or health impacts, offset ratios in emissions markets, and a Web-based analysis for quick pre-approval of proposed emission trades (Atkinson and Tietenberg 1987; Raufer 1998; Nash and Revesz 2001). Others who have looked at such restrictions are skeptical (Bernstein et al. 1994; Stavins 1997).

However, in the case of the OTC NO_x Budget, it is not clear that progressive flow control adequately addresses this problem of a mismatch between the time period of the environmental problem (2–5 day episodes) and the control period (5 months). Even small differences may be important because ozone concentrations are highly nonlinear functions of local NO_x concentrations. This potential problem may be exacerbated by the fact that power plant operation and several NO_x control technologies can be easily adjusted in near real-time and because restructuring has led to higher power prices when demand is greatest (Zhou et al. 2001; Blumsack et al. 2002).

2.3 Technology costs

NO_x control technologies can be divided into three rough categories: (1) combustion controls, (2) selective catalytic reduction (SCR), and (3) non-selective catalytic reduction (SNCR). Combustion controls (e.g., low- NO_x burners, overfire air) are used to change the shape, temperature profile, and air/fuel ratio of the flames in the boiler in order to minimize the amount of fuel and atmospheric nitrogen (NO_2) that is oxidized. The other two technologies are used to chemically reduce NO_x into molecular nitrogen (N_2) and water (H_2O) by spraying a nitrogen-based chemical reagent, usually urea (CH_4N_2O) or ammonia (NH_3), into the flue gas.

In the case of SNCR, reagent is introduced close to the boiler because the greatest NO_x reduction is achieved at temperatures between1,600-2,200°F. Multiple injection locations may be required to permit adequate control during partial load conditions. Typical SNCR technologies can lower NO_x emissions 30%–50% from coal-fired power plants, although more recent advances may give better performance. The capital costs for SNCR units are about $10–$20/kW for retrofits and half that for new construction, the difference being the need to modify boilers and flues during a retrofit. Operating costs associated with reagent, maintenance, and power requirements usually amount to $1–$2/MWh.

SCR controls are very similar, except that they contain beds of catalyst, usually made of a vanadium/titanium formulation (V_2O_5 stabilized in a TiO_2 base) and zeolite materials. The flue gas flows around and through these catalyst beds, speeding up the reduction reactions and allowing for much lower temperatures, 650°F–720°F. SCR technologies can lower NO_x emissions 70%–95% from coal-fired power plants. The capital costs for SCR units are about $50–$150/kW for retrofits and less for new construction, although very unit-specific difficulties in fitting an SCR unit into (or next to, or on top of) an existing power plant can drive those costs up. Operating costs associated with reagent, catalyst cost, maintenance, and power requirements usually amount to $4–$8/kWh, largely dependent on the catalyst's life.

Two important potential are problems associated with SCR and SNCR controls. The first is that the buildup of ammonium bisulfate on the pre-heater or other downstream components can reduce plant efficiency and may require maintenance to remove them. The second problem is that ammonia may contaminate the fly ash, which may make it difficult or unsafe to handle, and thus hard to sell to concrete makers or other buyers. Thus, careful, controlled operation of these technologies is required to maximize plant operation and revenue.

Under these conditions, power plant operators may respond to economic incentives in both the production of electric power and the management of NO_x emissions, possibly turning NO_x controls down when electricity prices are highest in order to increase electricity production (and therefore revenue), or possibly shifting from one plant to another as fuel prices change, thus changing the rate and mass of NO_x emissions during hot summer days. Such actions could lead to higher levels of air pollution than would be expected under a command-and-control approach, and raise the question of whether the periodicity of the NO_x Budget gives firms too much temporal flexibility even with progressive flow control (Farrell, Carter et al. 1999).

The overall effects of the NO_x Budget Program are described in the EPA's annual compliance reports for the OTC NO_x Budget program, which provide aggregate results, including the number of units regulated, ozone season emissions and allowance allocations (by state and total), the number of banked allowances (total), noncompliance issues, and the progressive flow control ratios.[4] This analysis goes somewhat deeper by examining data at a much more fine level of temporal detail (hourly).

[4] EPA. Clean Air Markets - Progress and Results. Compliance Reports. http://www.epa.gov/airmarkets/cmprpt/index.html

3. Market Analysis

This section of the report analyzes the effect of emission allowances and other factors on the behavior of market participants. Qualitative data was gathered from interviews with participants in the NO_x Budget Program, including regulators, managers in regulated firms, and brokers. Electric power plant and other plant configuration information were compiled from several sources, including EPA's *E-GRID* database, several EIA reports and publicly available material provided by firms with facilities regulated by the NO_x Budget. Unit-specific, hourly NO_x emissions data for all sources in the OTC NO_x Budget for 1998–2001 were obtained from Resource Data International (RDI). Weekly NO_x allowance prices were obtained from several brokers and industry trade publications, especially *Air Daily*, for 1998–2003. Hourly electricity data (demand, generation, imports, and prices) were obtained from the Independent System Operators (ISO) for the New England (NE), New York (NY), and Pennsylvania-New Jersey-Maryland (PJM) interconnects. Fuel prices were obtained from RDI and the New York Mercantile Exchange.[5]

Insights from the interviews and literature review were used to guide the several quantitative analyses that followed. There are 907 ”sources” in the OTC NO_x Budget Program, which, in 2000 had emissions of 952,049,548 lbs. This study focused on ”large” (> $100MW_e$) electric power plants and co-generators, which accounted for 773,530,680 emissions in 2000, or 81% of all regulated emissions. This data set contained 476 units combined in 137 plants. A part of this analysis considered only power plants and not co-generators and part considered only plants in PJM, due to data availability. Data from 1998–2000 was used. Table 1 shows some of the details of large power plants in the OTC states and post-combustion NO_x controls.

Table 1. Large (> 100MW) power plants (not co-generators) in the OTC States

	Number of Units	Capacity (MW)	Post-Combustion NO_X Controls (2002)	
			SCR	SNCR
Connecticut	26	3767	1	2
Washington DC	2	550	-	-
Delaware	13	2149	-	1
Massachusetts	27	6891	3	1
Maryland	48	8386	2	1
New Hampshire	9	1034	2	-
New Jersey	67	8157	2	2
New York	153	16519	4	-
Pennsylvania	64	15962	3	-
Rhode Island	6	1127	4	-
Total	**415**	**64542**	**21**	**7**

[5] Relevant URLs include: http://www.epa.gov/airmarkets/egrid/, http://www.eia.doe.gov/fuelelectric.html, http://www.emissions.org/, http://www.energyargus.com/, http://www.epa.gov/airmarkets/tracking, http://www.iso-ne.com/, http://www.nyiso.com/, and http://www.pjm.com/ .

The first quantitative analysis compared key values in terms of emissions and emissions rates for various periods. Because power plant emissions are closely associated with generation, comparisons to control for the effect of changes in demand were made. In addition, because emissions during ozone periods are of greatest importance in terms of human health, these periods were identified and compared as well. The second quantitative analysis consisted of a series of Ordinary Least Squares (OLS) regressions designed to more rigorously investigate possible reasons for observed changes in NO_x emissions during the course of the year. Again, greatest focus was given to the periods during which NO_x emissions have the greatest potential impact on human health—ozone episodes.

4. Results

The interviews with the participants in the OTC NO_x Budget Program indicated a wide variety of opinion. The early years of this market (1997–2000) occurred in a very different world—this was while the dot-com stock market bubble and electricity industry restructuring were underway, and before the financial scandals associated with Enron and some electric power markets. A key finding of this study was that virtually every firm with a requirement to reduce emissions took a conservative approach to the trading of emissions allowances. They traded relatively infrequently and generally did not rely on the market very much for compliance.

Reluctance to rely on the NO_x Allowance market came from several sources. Perhaps most importantly, market participants perceived very large uncertainties in the market, especially over the ability to purchase allowances. The relatively small number of potential participants in the NO_x market and, over time, the observation that relatively few transactions occurred during most weeks, meant both buyers and sellers were concerned that their own participation in the market could change market prices, generally in an unfavorable direction. The slow pace of the allowance market may have been enhanced by a somewhat hurried start of the program in 1999 and the lack of mechanisms for early price discovery, such as allowance auctions (Farrell 2000). Uncertainties were also introduced by the PFC provisions, and lawsuits (especially in Maryland) in 1998–1999.

Another reason for reluctance to rely on the market was that most firms thought of the NO_x Budget program as a regulatory issue for which the most appropriate concept is compliance, rather than a market opportunity for which the most appropriate concept would be profitability. The relatively low cost of the program relative to electricity markets at the time may also have contributed to this notion. For instance, using average values for the 2000 ozone season, NO_x emission allowances were priced at \$0.40/MWh, while electricity prices averaged \$42/MWh and peaked at over \$1,500/MW in at least one market. Given these incentives, it is likely that power plant operators would focus on reliability in generating electricity over making slight changes to the emissions control equipment to optimize NO_x control costs. The structure of contracts in electricity markets would tend to reinforce this effect, since they punish both over- and under-generation relative to the amount promised in day-ahead markets. Interviews with market participants and power plant operators supported these arguments. Thus, many firms with regulated sources participated in the NO_x market only occasionally, whenever their total environmental compliance plan was modified, which might happen only once or twice per year.

An exception to this observation of low participation can be found in speculators in the NO_x Allowance Market, including Enron, Arizona Power System, and individual trading desks at some regulated firms. Speculative activities were not uncommon in the first few years of the market but became more rare after 2001, as many markets slowed.

The results of the first set of quantitative analyses are discussed next. Table 2 shows a variety of emissions values as well as generation for the ozone seasons (May–September) in 1998–2001. This information is shown in graphical form in Figure 3. The data has been normalized in the tables to allow all the relevant values to be shown on the same figure. Total emissions over the NO_x season (tons) declines in each year, and declines substantially (by almost 25%) in the first year of the program from the pervious year. Similarly, the average emission rate (lb/hr) declines every year. However, the peak emission rate recorded over any single hour during the ozone season at first declines by about 15% from 1998 to 1999 and then rises again, although never rising higher than pre-program levels. The peak emission rate may be a better indicator of the impact of the OTC NO_x Budget program than the seasonal values because of the episodic nature of the ozone problem.

Table 2. Ozone season NO_X emissions and generation

Year	Emissions (tons)	Avg. NO_X rate (lb./hr)	Peak NO_X rate (lb./hr)	Avg. NO_X rate (lb./MWh)	Peak NO_X rate (lb./MWh)	Generation (GWh)
1998	156,484	83,310	134,947	2.9	20.0	108,799
1999	120,048	63,082	115,628	2.1	8.2	118,107
2000	117,025	60,640	124,125	1.2	5.5	134,390
2001	111,043	57,223	126,556	1.1	3.0	131,521

Note: These data are for all power plants, including those in Maryland that only participated in the 2000 and 2001 NO_X Budget program.

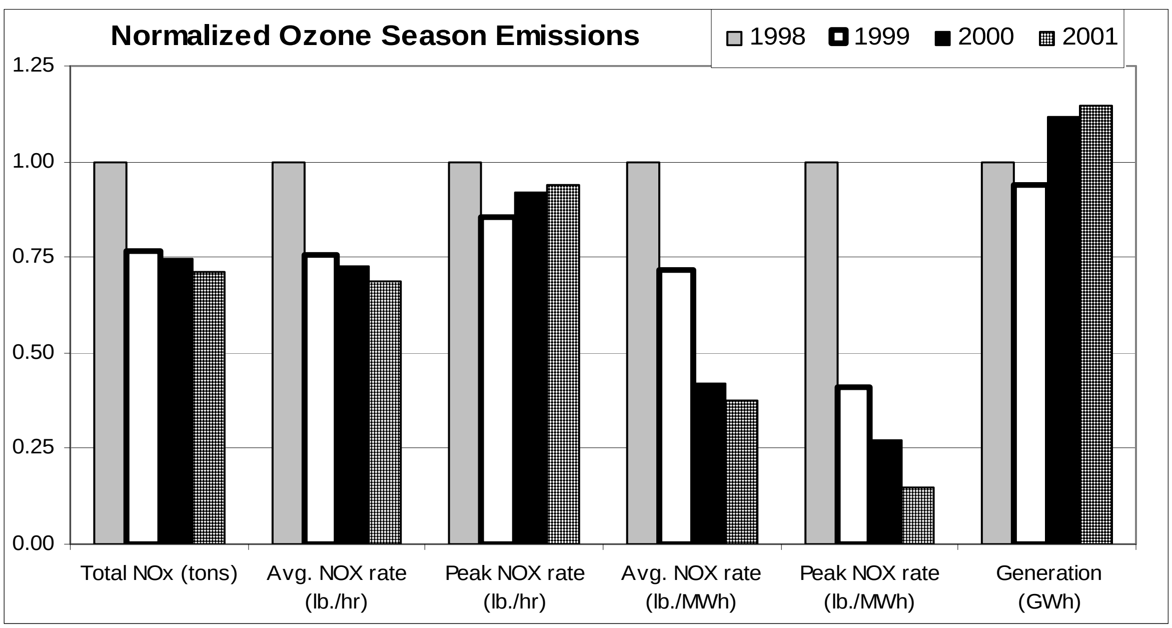

Figure 3. Normalized emissions during the ozone season

Also significant are the very substantial declines in emissions per unit of output (lb./MWh, or emission factor), which is a result of both declining emissions and rising generation. This analysis shows that the large (> 100MW) power plants in the OTC NO_x Budget controlled emissions, on aggregate, more each of the first three years of the program. Similar (but less strong) trends are seen in annual emissions data (not shown here).

Table 3 and Figure 4 present emissions and generation for the worst ozone episode in each year, as measured in New York City (which is roughly in the center of the OTC states). Peak ozone concentrations ranged from 0.142–0.171 parts per million (ppm), compared to the health standard of 0.120 ppm. Two episodes lasted three days (2000 and 2001), and two lasted four days (1998 and 1999), making the total tons and total generation results less easily comparable.

Table 3. Ozone episode NO_X emissions and generation

Year	Emissions (tons)	Avg. NO_X rate (lb./hr)	Peak NO_X rate (lb./hr)	Avg. NO_X rate (lb./MWh)	Peak NO_X rate (lb./MWh)	Generation (GWh)
1998	5,670	91,996	121,570	3.0	4.9	3,374
1999	4,238	85,038	110,573	2.8	5.5	2,980
2000	2,483	65,658	83,643	1.2	1.7	2,135
2001	3,801	100,976	126,556	1.8	3.0	3,177

Notes: These data are for the worst ozone episode in each year, which were of different lengths.

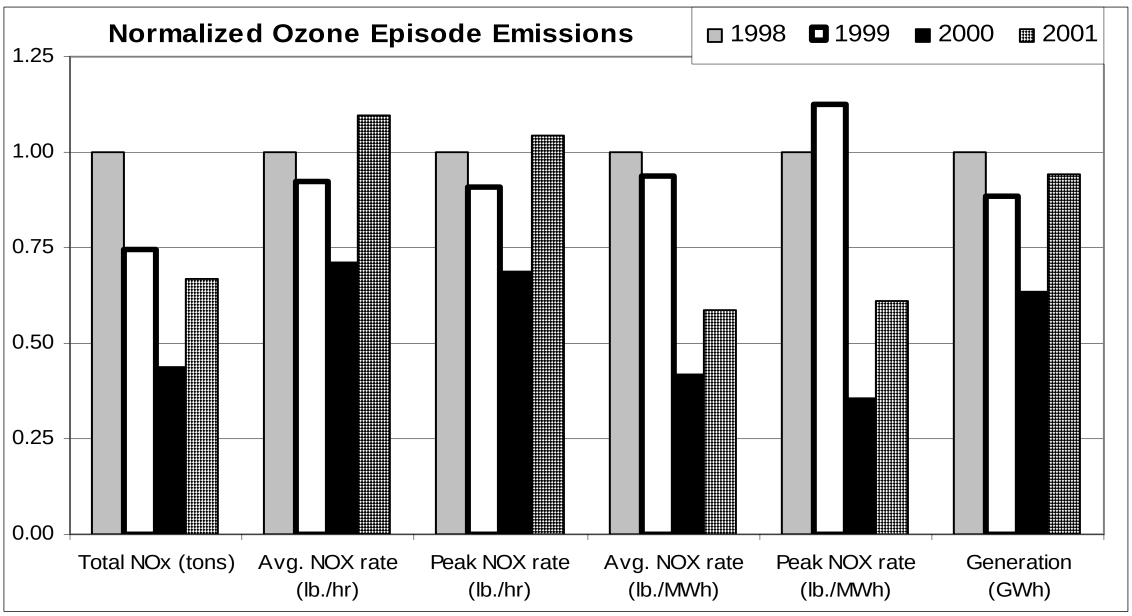

Figure 4. Emissions and generation for the worst ozone episodes in four years

As with the ozone season analysis, total emissions during ozone episodes periods decreased with the NO_x Budget, but they have not declined each year since 1998. However, the average and peak NO_x emission rates (lb/hr) are highest in 2001, while the peak emission factor (lb/MWh) is highest in 1998. More tellingly, average generation (in MW, not shown) during these episodes is considerably (12%–80%) higher than during the ozone season as a whole. Further, comparing between Tables 1 and 2, it can be seen that the absolute magnitudes of the average NO_x emission rates (lb/hr) are substantially (8% to 77%) higher during the ozone episodes than during the entire ozone season in which they occur.

One reason for the high emission rate in 2001 is that electricity demand for this period (August 7–9) was extremely high. Total generation for these three days was greater than that for the four-day long ozone episode of 1998 (3.18 GWh compared to 2.98 GWh), while peak generation was even more exceptional (52 GW compared to 37–39 GW for the other three episodes). At the same time, the 2001 ozone episode was the least severe, with a peak concentration of 0.142 ppm.

This analysis suggests two things. First, NO_x emissions under a C/T system are strongly correlated with electricity generation. This is particularly important because the same is true of traditional command-and-control regulation, the most reasonable alternative . Second, power plant NO_x emissions in the Northeast are not always determinative of the level of smog problems in the area.

While an increase in emission rates due to increased electricity demand (and thus increased generation) would occur under both C/T and traditional command-and-control regulation, it may still be the case that plants take advantage of the temporal flexibility and change their operations during ozone episodes or other periods (such as when electric power prices are higher. Aggregate comparisons here are difficult in particular because to a significant degree, NO_x emissions depend on which specific power generators are operating at any give time. One approach would be to look at periods with similar total power generation, when the units operating would be roughly similar.

This approach is taken with Table 4 and Figure 5, which present data for four 3-day periods with generation close to the 3-day period containing the worst ozone episode in 2000 (00e). The first two are also taken from 2000, one period during the ozone season (00s in Table 4) and one period is not during the ozone season (00n). The second two are from the ozone seasons in 1999 and 2001 (99 and 01, respectively). While not a perfect control, this should reduce the differences due to having different generators running for any given period, assuming dispatch order does not change appreciably.

Table 4. Emissions and generation for periods comparable to a 2000 ozone episode

Period	Emissions (tons)	Avg. NO_X rate (lb./hr)	Peak NO_X rate (lb./hr)	Avg. NO_X rate (lb./MWh)	Peak NO_X rate (lb./MWh)	Generation (GWh)
00e	2,483	65,658	83,643	1.2	1.7	2,135
00s	2,236	59,217	87,471	1.2	1.4	1,916
00n	3,613	95,527	113,253	2.6	3.6	2,315
99s	2,766	74,117	101,968	2.6	3.2	1,880
01s	2,008	52,917	82,768	1.1	1.6	1,820

Note: Table contains data for four 3-day periods with total generation close to the worst ozone episode in 2000, 6/9–6/11, labeled 00e. Period 00s occurred during the 2000 ozone season. Period 00n occurred during 2000 but not during the ozone season. Period 99s and 01s occurred during the 1999 and 2001 ozone seasons.

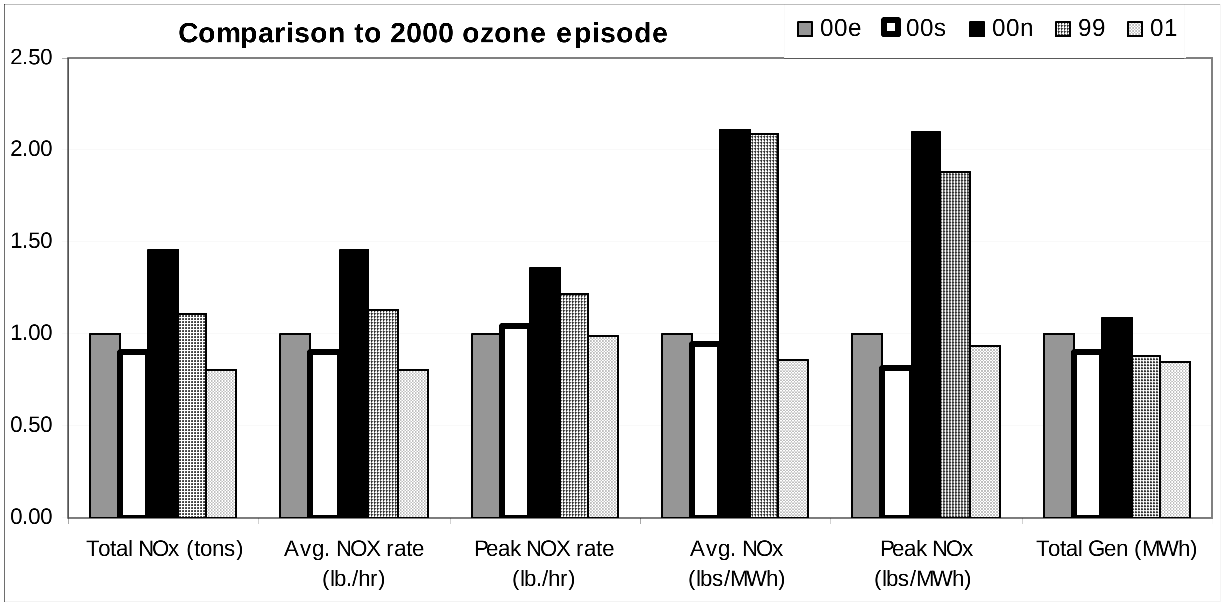

Figure 5. Emissions and generation for periods comparable to a 2000 ozone episode

Emissions in the non-ozone season comparison period (00n) are substantially higher than those during the season, which is expected. Differences in terms of the emission factor (lb/MWh) are greatest, which is important, because this metric reflects changes in dispatch and plant operation and is independent of amount of electricity generated. The emissions of the other two comparison periods (00s and 01s) suggest, on the contrary, very similar dispatch and plant operation. These data suggests that the NO_x Budget Program does not tend to change how plants are operated. To test this definitely, however, a more rigorous approach is needed.

A set of OLS regression models were developed to look for changes in large (> 100MW) power plant operation due to the OTC NO_x Budget program. Data for 2000 was used. This analysis proceeded in three steps.

First, several models were estimated using data for all the large plants in the OTC region. The second step consisted of using the same models with data from large plants in Pennsylvania, Jersey, Maryland (PJM) and specifying additional models with variables for electricity prices, which were available for the entire year only for PJM. Power plants in the PJM interconnect account for a majority (55%) of electricity capacity in the entire OTC region, so these results are reasonably representative of the overall outcomes.

The results from the first two steps are presented in Tables 5 and 6 below. The models are specified to use generation, fuel prices, electricity prices, and the OTC NO_x Budget to explain hourly ozone emissions. Various specifications were used; those shown here demonstrate the results best. All of the coefficients are significant at the 0.001 level, and all have the expected sign, save two minor exceptions.

Model 1 consists only of a variable for electricity generation at power plants (excluding co-generators for the OTC data) and a constant. Even this simple model achieves high explanatory power (R^2 values of 0.64 for the OTC and 0.78 for PJM). This confirms the earlier assumption that electricity generation would be a good predictor for emissions. Model 2 adds a dummy variable that takes a value of one for hours during the ozone season and a value of zero otherwise. The predictive power of these models is significantly stronger (R^2 values of 0.84 for the OTC and 0.96 for PJM). These results strongly suggest that the OTC NO_x Budget has had a very strong affect on emissions from large power plants, which is unsurprising.

More important, Models 3–6 add fuel and electricity prices (and co-generators for the OTC data) to Models 1 and 2. Although the coefficients for these specifications are significant and improve the predictive power of the regression models *without* the ozone season dummy variable (Models 3 and 5), they have very little or no effect when the dummy is *included* in the model (Models 4 and 6). This strongly suggests that fuel and electricity prices have little or no effect on NO_x emissions of large power plants in the OTC NO_x Budget program relative to the requirements of the program itself. Very similar results are obtained with a variety of specifications and when allowance prices are included.

Table 5. Regression models for large OTC plants for all of 2000

Model 1-OTC					
Variable	Coefficient	*t* – statistic	*p* – value		
POWERGEN	3.10	175	0	N	8,760
Constant	5,100	13	0	R^2	0.78
				Adj. R^2	0.78

Model 2-OTC					
Variable	Coefficient	*t* – statistic	*p* – value		
POWERGEN	3.37	373	0	N	8,760
D_SEASON	-16,600	-162	0	R^2	0.94
Constant	6,400	34	0	Adj. R^2	0.94

Model 3-OTC					
Variable	Coefficient	*t* – statistic	*p* – value		
POWERGEN	2.94	234	0	N	8,760
COGEN	3.79	66.0	0	R^2	0.90
COALPRICE	192,000	29.6	0	Adj. R^2	0.90
GASPRICE	-5050	-18.0	0		
Constant	-243,000	-27.0	0		

Model 4-OTC					
Variable	Coefficient	*t* – statistic	*p* – value		
POWERGEN	3.33	381	0	N	8,760
COGEN	-.427	-8.05	0	R^2	0.96
COALPRICE	104,000	24.5	0	Adj. R^2	0.96
GASPRICE	-1,870	-10.3	0		
D_SEASON	-16,900	-111	0		
Constant	-35,200	-9.36	0		

Table 6. Regression models for large PJM plants for all of 2000

Model 1-PJM					
Variable	Coefficient	*t* – statistic	*p* – value		
POWERGEN	3.00	125	0	N	8,760
Constant	-27,800	-40	0	R^2	0.64
				Adj. R^2	0.64

Model 2-PJM					
Variable	Coefficient	*t* – statistic	*p* – value		
POWERGEN	3.24	200	0	N	8,760
D_SEASON	-14,400	-104	0	R^2	0.84
Constant	-287,00	-61	0	Adj. R^2	0.84

Model 5-PJM					
Variable	Coefficient	*t* – statistic	*p* – value		
POWERGEN	3.07	108	0	N	8,760
ELECTPRICE	-16.3	-4.2	0	R^2	0.64
Constant	-29,200	-37.9	0	Adj. R^2	0.64

Model 6-PJM					
Variable	Coefficient	*t* – statistic	*p* – value		
POWERGEN	3.18	167	0	N	8,760
ELECTPRICE	15.6	5.98	0	R^2	0.84
D_SEASON	-14,500	-104	0	Adj. R^2	0.84
Constant	-27,400	-53	0		

The third step in the regression analysis applied Model 3 to data from the worst ozone episode in 2000 and two other periods in that year of the same duration with very similar total electricity generation, one during the ozone season and one not during the ozone season. This analysis parallels the analysis above associated with Table 4 and Figure 5. The key regression results are presented below in Table 7. The R^2 values for these models are extremely high, but the sign and significance of most of the variables change from one model to another. Only the coefficient for electricity generation is significant and has the expected sign in all three models. This suggests that generation can be an extremely good predictor of NO_x emissions over short periods of time, and that some of the residuals in other (annual) models applied to annual data may be associated with the operation of different power plants over the course of the year due to scheduled (and unscheduled) maintenance. If it is assumed that within each of the three-day periods that the same power plants are operated, the results in Table 7 indicate extremely stable operation. The idea that power plant operators might change plant operation as electricity prices change over the course of the day (power prices often have a diurnal pattern) is not supported by this analysis.

Interesting (but less obvious) are the values taken by the generation coefficient in the three models shown in Table 7. For comparison, the coefficient found using annual data is 2.94 (see Table 5). The coefficient for the ozone episode (00c) is lower, while the coefficient for the in-season comparison (00d) is close to the annual value and the coefficient for the non-season (00e) value is higher. (The coefficient for generation when Model 3 is applied to October–December data is similar to the non-season value.) A higher value for the non-season coefficient is expected, since this implies that power plants in the OTC produce more NO_x when the NO_x Budget program is not in force, which was observed in Models 2, 4, and 6. However, it is not so clear why the value for the ozone episode itself should be so low. Investigating more ozone season comparisons or using a disaggregated analysis may be needed to resolve this issue.

Nonetheless, this third step of the regression analysis provides no support for the idea that the NO_x Budget program has led to increased emissions during ozone episodes, undercutting concerns about changes in power plant operation.

Table 7. Regression models for large PJM plants for 2000

Model 3-00e: ozone episode					
Variable	Coefficient	*t* – statistic	*p* – value		
POWERGEN	2.27	12.6	0	N	72
COGEN	2.71	1.94	0.057	R^2	0.98
COALPRICE	-12,800	-0.877	0.384	Adj. R^2	0.98
GASPRICE	-205	-0.230	0.818		
Constant	213,000	38.7	0.228		
Model 3-00s: comparison during ozone season					
Variable	Coefficient	*t* – statistic	*p* – value		
POWERGEN	3.01	19.1	0	N	72
COGEN	1.74	1.47	0.240	R^2	0.99
COALPRICE	37,900	4.30	0.0001	Adj. R^2	0.99
GASPRICE	114	4.59	0		
Constant	-517,000	-4.37	0		
Model 3-00n: comparison not in the ozone season					
Variable	Coefficient	*t* – statistic	*p* – value		
POWERGEN	4.02	23.6	0	N	72
COGEN	-2.81	-2.82	0.0062	R^2	0.96
COALPRICE	-2,830	-0.208	0.836	Adj. R^2	0.96
GASPRICE	41.4	0.195	0.846		
Constant	58,100	0.339	0.736		

5. Conclusions

The analysis of the OTC NO_x Budget presented here supports several conclusions that may be relevant to other emission trading markets.

First, this emission trading program has been effective in achieving the proximate goals set out for it in reducing emissions. And it appears that it has made substantial contributions to more long-term goals of improving human health and the environment.

Second, the OTC NO_x Budget market has had relatively limited numbers of transactions (i.e., it has been fairly "thin"), ranging from zero to perhaps several dozen per week.[6] The number of allowances changing hands in a given week was often less than one thousand—well under one percent of all allowances. This relatively illiquid market was able to establish fairly stable price levels and respond relatively quickly to new information. It appears that there tended to be significant, but very temporary, increases in prices just before new emission limits came into effect—either by a lower cap being imposed on existing participants or by new participants being regulated. The main difficulty of thin markets appears to be for large participants, who find it challenging to make large trades that will be sufficiently meaningful to them without changing allowance prices. It may be that the thinness of the NO_x Budget program is related to the fact that a relatively few number of sources and firms were participants. As the market evolved into the NO_x SIP market, trading levels seemed to grow somewhat and concerns about thin markets faded.

Third, there is little evidence that regulated entities changed their patterns of behavior based on short-term changes in allowance prices. This appears partly due to the fact that some of participants who were in a position to do so technologically were more concerned during the first several years of the program with ensuring that the emission control technologies worked correctly and did not interfere with production or generation. It may also be partly due to the fact that the implied costs of emission controls was not very high for most of the time. No interview or statistical evidence was found in the 2000 ozone season that operators of large power plants respond to fuel or electricity prices by adjusting (in aggregate) plant operation to change NO_x emissions. This result is further supported by the comparison of a specific ozone episode with periods similar from an electric generation standpoint. Power plants appear to operate the same during high ozone periods as other periods of the year.

This report illustrates that it is possible for states to implement matching emissions trading programs that function through a single market and can effectively reduce emissions. This success was possible in the case of the OTC NO_X Budget despite several imperfections, including the complexity and uncertainty associated with Progressive Flow Control and a somewhat hurried start to the program. However, these problems likely reduced participation in the market and may have reduced the efficiency of the program. Similarly, the costs of monitoring and reporting, especially for sources that did not already have some of this capability already, may have reduced participation in the market somewhat. Reducing the costs, complexity

[6] These are economically significant transactions—those that occurred between accounts held by distinct and unrelated entities and not associated with the sale of the asset (e.g., an EGU) to which those allowances were originally allocated.

and uncertainty associated with emissions markets would be good ways to improve their efficiency. One way to do this might be for regulators to collect and distribute more information, including price information, or to hold auctions to generate more information.

6. References

Atkinson, S. E. and T. Tietenberg (1987). "Economic Implications of Emissions Trading Rules for Local and Regional Pollutants." Canadian Journal of Economics **20**: 370.

Bernstein, M., A. Farrell, et al. (1994). "The Environment and Economics: The Impact of Restricting the SO2 Allowance Market." Energy Policy **22**(9): 748-754.

Blumsack, S., D. Perekhodstev, et al. (2002). "Market Power in Deregulated Wholesale Electricity Markets: Issues in Measurement and the Cost of Mitigation." Electricity Journal **15**(9): 11-24.

Burtraw, D., K. Palmer, et al. (2001). "Cost-effective reduction of NO_x emissions from electricity generation." Journal of the Air & Waste Management Association **51**(10): 1476-1489.

Bush, G. W. (2002). Clear Skies Initiative. Washington, DC, The White House.

Dorris, G., J. Agras, et al. (1999). Development and Evaluation of a Targeted Emission Reduction Scenario for NO_x Point Sources in the Eastern United States: An Application of the Regional Economic Model for Air Quality (REMAQ). Washington, DC, U.S. Environmental Protection Agency.

Farrell, A. (2000). "The NO_x Budget: A Look at the First Year." Electricity Journal **March**: 83-92.

Farrell, A. E. (2004). Review of Emission Trading for Consideration of Applications in California. California Climate Change Center. Berkeley**:** 26.

Farrell, A. E., R. Carter, et al. (1999). "The NO_x Budget: Costs, Emissions, and Implementation Issues." Resource & Energy Economics **21**(2): 103-124.

Fromm, O. and B. Hansjurgens (1996). "Emission trading in theory and practice: an analysis of RECLAIM in Southern California." Environment and Planning C: Government and Policy **14**: 367-384.

ICF Resources (1995). Estimated Effects of Alternative NO_x Cap and Trading Schemes in the Northeast Ozone Transport Region, ICF Kaiser.

Metcalfe, S. E., R. G. Derwent, et al. (1998). "Nitrogen deposition and strategies for the control of acidification and eutrophication across Great Britain." Water, Air and Soil Pollution **107**(1-4): 121-145.

Milford, J. B., D. F. Gao, et al. (1994). "Ozone Precursor Levels and Responses to Emissions Reductions - Analysis of Regional Oxidant Model Results." Atmospheric Environment **28**(12): 2093-2104.

Nash, J. R. and R. L. Revesz (2001). "Markets and geography: Designing marketable permit schemes to control local and regional pollutants." Ecology Law Quarterly **28**(3): 569-661.

National Research Council - Committee on Tropospheric Ozone Formation and Measurement (1991). Rethinking the ozone problem in urban and regional air pollution. Washington, DC, National Academy Press.

Office of Air and Radiation (2003). 2002 OTC NOx Budget Program Compliance Report. Washington DC: U.S. Environmental Protection Agency. 5.

Ozone Transport Commission (2003). OTC NOx Budget Program: 1999-2002 Progress Report. Washington, DC. 19.

Possiel, N. C. and W. M. Cox (1993). "The Relative Effectiveness of NO_x and VOC Strategies In Reducing Northeast U.S. Ozone Concentrations." Water, Air, and Soil Pollution **67**: 161-179.

Raufer, R. (1998). Pollution Markets in a Green Country Town: Urban Environmental Management in Transition. Westport, CT, Praeger Publishers.

Shindell, D. T., G. Faluvegi, et al. (2003). "Preindustrial-to-present-day radiative forcing by tropospheric ozone from improved simulations with the GISS chemistry-climate GCM." Atmospheric Chemistry and Physics **3**: 1675-1702.

STAPPA/ALAPCO (1994). Controlling Nitrogen Oxides Under the Clean Air Act: A Menu of Options. Washington, DC, State and Territorial Air Pollution Program Administrators / Association of Local Air Pollution Control Officials. **July**.

Stavins, R. (1997). "What can we learn from the grand policy experiment? Lessons from SO2 allowance trading." Journal of Economic Perspectives **12**(3): 69-88.

Swift, B. (2001). "How Environmental Laws Work: An Analysis of the Utility Sector's Response to Regulation of Nitrogen Oxides and Sulfur Dioxide Under the Clean Air Act" Tulane Environmental Law Journal. 14(Summer): 309-425.

Zhou, H., K. F. Cen, et al. (2001). "Combining neural network and genetic algorithms to optimize low NO_x pulverized coal combustion." Fuel **80**(15): 2163-2169.